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Technical Report ARFSD-TR-90029

BASIC SIMPLE MODELING OF BALLOTING MOTION OF RAILGUN PROJECTILES

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July 1991

US ARMY
ARMAMENT MUNITIONS
& CHEMICAL COMMAND
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U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Fire Support Armaments Center

Picatinny Arsenal, New Jersey

REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE July 1991	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

A BASIC SIMPLE MODELING OF BALLOTING MOTION OF RAILGUN PROJECTILES

5. FUNDING NUMBERS

6. AUTHOR(S)

Szu Hsiung Chu

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

ARDEC, FSAC
Electric Armaments Division (SMCAR-FSE)
Picatinny Arsenal, NJ 07806-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

Technical Report ARFSD-TR-90029

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ARDEC, IMD
STINFO Br
ATTN: SMCAR-IMI-I
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

This is the second of three basic reports dealing with the in-bore balloting motion of a projectile launched in an electromagnetic railgun.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This is the second of three basic reports dealing with the in-bore balloting motion of a projectile launched in an electromagnetic railgun. The first report addressed axial projectile motion without cocking and was titled "A Basic Simple Model of In-bore Motion of Railgun Projectiles."

Understanding the in-bore motion of a projectile is important to its design and its ability to hit a target with some effectiveness. Analysis of in-bore motion is a complicated problem since many parameters are involved and the interacting relationships between them must be determined. To make the problem easier to understand, it was analyzed on several levels beginning with the basic simple model which computed only the axial motion and followed by more complicated models in the upper analysis levels that included as many lateral forces and gun tube vibration effects as possible.

This report deals with the second basic or zero level of balloting analysis. A basic simple model considering only the effect of the propulsion force, the friction force of the armature, and the clearance between the projectile and the barrel is presented. The computation of the axial projectile motion with a certain cocking angle is the goal of this analysis. Equations of motion are derived and solved. A sample computation with available data is performed and the results plotted to give a clearer understanding of balloting action.

14. SUBJECT TERMS

In-bore motion   Balloting   Gun dynamics   Projectile   Railgun

15. NUMBER OF PAGES 23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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INTRODUCTION

This is the second of three basic reports addressing the in-bore balloting motion of a projectile launched in an electromagnetic railgun. The first report of this series (ref) addressed axial projectile motion without cocking and included the derivation of basic equations for calculating projectile acceleration and velocity. In order to make this presentation easier to understand and more complete, some statements that were discussed in the first report are repeated in this report.

In-bore motion of a projectile is the start of the subsequent motion of the projectile. It affects the lateral impact of the projectile on the barrel, muzzle jump, intermediate and terminal ballistics and, consequently, the accuracy of the projectile of hitting the target after it leaves the gun. The lateral impacts of the projectile on the barrel during in-bore motion also would affect the more sensitive components of some projectiles such as those containing electronics. The force structure and in-bore projectile dynamics are an important concern in the development of an armament system for an electromagnetic launcher since the average accelerations are much larger and the length of the barrel may be longer. In addition, unlike for a conventional gun, the circumferential construction of the barrel is not uniform, complicating the analytical work.

This basic analysis of the railgun projectile balloting motion is simplified by ignoring many complicated effects, such as the compression effect of the projectile, air resistance, barrel expansion, gun vibration, elastic deformation, and thermal effect. Thus, only a simple axial motion with a certain cocking angle is considered. The propulsion force is assumed to be a known quantity. The friction forces between the armature and the barrel and the bourrelet and the barrel are included. The effect of the armature and projectile weights are considered. Consequently, the equations of motion are formulated by considering the cocking projectile in an axial dynamic equilibrium condition under the action of the above-mentioned forces. The normal motion is ignored.

The solutions to the derived equations are obtained by either closed form or numerical methods. The first step of solution is to determine the cocking angle and some friction forces. The acceleration and the normal reactions are then computed by solving simultaneous equations. After this, the velocities and displacements are obtained by the integration technique or numerical methods. The results provide a basic idea of the in-bore cocking condition of the projectile.

A sample calculation is given with the available required data. Figures are included to show some of the computed results with respect to time or projectile travel.

DISCUSSION

Assumptions

The following assumptions are made to compute the cocking angle and associated normal reaction forces.

The projectile and the armature are assumed to be integrated into one projectile package. The contact of the projectile package with the barrel is taken to be on the armature and the bourrelet portion only, and they are considered as point contacts. The center of armature base is assumed to always move along the centerline of the barrel. No leakage occurs around the armature. Thus there is uniform pressure along the circumference and a normal reaction force acting at the armature and the bourrelet respectively. These two forces produce friction along the circumference and at the contact points. The propulsion force is applied uniformly to the rear face of the armature so that the resultant propulsion force is acting on the armature base center. It is coinciding and directed along the barrel centerline. The mass center of the projectile package may have an offset, ε, from its geometrical centerline. All components such as the barrel, projectile and the armature are considered to be rigid except for that portion of the bourrelet contacting the barrel. The impact effect is ignored. The projectile is considered to always contact the rail at the armature and the bourrelet contact points. The resultant of the air drag force is considered to be acting at the mass center of the projectile. The air lift force and moment are ignored. The rotational effect of the projectile is neglected in this analysis, but it will be considered later.

Although the armature is always in contact with the rail and the center of the armature is always at the centerline of the barrel, the diameter of the bourrelet may be smaller than that of the bore. Thus, there is some clearance between the bourrelet and the rail and the projectile may cock inside the barrel even though there is no compression at the bourrelet. However, the cock angle is assumed to be small and the bourrelet-barrel contact assumed to be a point contact to simplify the analysis as mentioned before.

To further simplify the analysis, all forces or their resultants are assumed to be in one plane containing the center of projectile package mass, and centerline of rails, projectile, barrel, and the bourrelet-barrel contact point. Consequently a plane motion is analyzed. The resultant forces normal to the barrel centerline are computed in addition to the frictional forces and the Lorentz force.

Coordinate System

A right-handed Cartesian coordinate system is used in this analysis as shown in figure 1. The x-axis is taken to the centerline of the barrel and the y-axis is normal to the barrel and pointing upward in a vertical plane. The origin of the coordinate system is located at the breech. The x-axis or the barrel may have an inclination angle, α, with respect to the horizon (usually referred to as the angle of elevation) as shown in the figure.

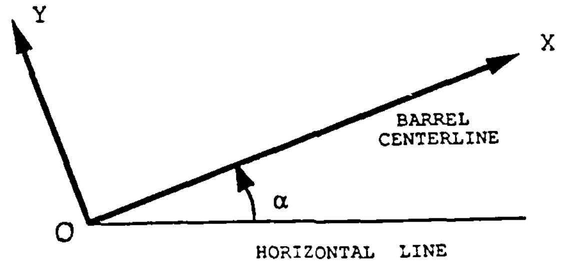

Figure 1. Coordinate system

Governing Equations

From the above-mentioned conditions and the coordinate system, equations of equilibrium are derived from dynamic and static equilibrium of forces in a plane. When the projectile is cocked inside the barrel, the assumed interacting condition is shown in figure 2. Note that the fore and aft bore rider of a saboted projectile correspond to the bourrelet and the armature portion of a projectile without a sabot, respectively.

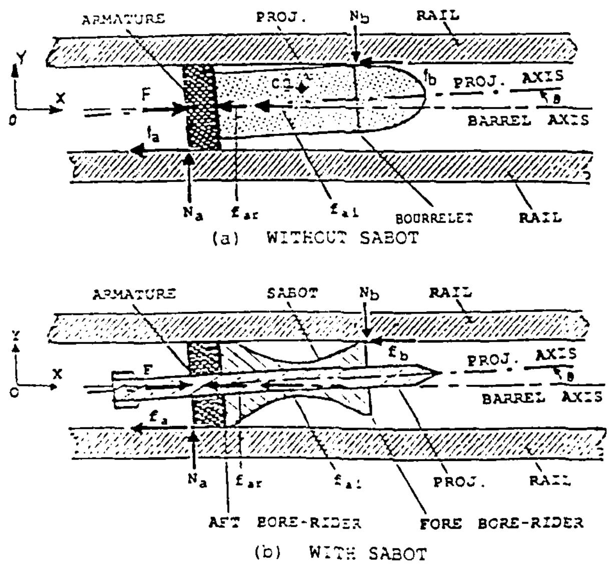

Figure 2. Barrel and projectile package configuration showing propulsion and interacting forces

The forces acting on the projectile are all shown in the figure except the air drag force and the gravitational force which acts at the projectile center of gravity (c. g.), and has components along and normal to the centerline of the barrel. Under the action of these forces, the governing equations formulated from Newton's second law of motion are as follows:

For the x-direction or axial motion, the equilibrium equation is

$$ma = F - f_{ar} - f_{ai} - f_a - f_b - D - mg\sin\alpha \tag{1}$$

For the forces in the y-direction, the equilibrium equation is

$$0 = N_a - N_b - mg\cos\alpha \tag{2}$$

For the cock or yaw condition, the equilibrium equation is

$$\begin{aligned} 0 = {} & y(F - f_{ar} - f_{ai}) - N_a(\ell\cos\theta - R\tan\theta - \varepsilon\sin\theta) \\ & - N_b[h\cos\theta + \varepsilon\sin\theta - (r - \delta_b)\sin\theta] \\ & - f_a(R + y) + f_b(R - y) \end{aligned} \tag{3}$$

The y coordinate of the c. g. of the projectile package is

$$y = \ell\sin\theta + \varepsilon\cos\theta \tag{4}$$

where

- m = mass of projectile package or sum of masses of armature and projectile
- a = axial or x-direction acceleration of projectile package
- y = y coordinate of projectile c. g.
- F = total propulsion or Lorentz force
- f_{ar} = resultant friction force between armature and rail due to uniform circumferential compression
- f_{ai} = resultant friction force between armature and insulator due to uniform circumferential compression
- f_a = friction force between armature and rail due to normal reaction force
- f_b = friction force between bourrelet and rail due to normal reaction force
- D = drag force of air resistance (aerodynamic drag)
- g = gravitational constant = 9.81 m/sec/sec
- α = inclination of x-axis or barrel with respect to the horizon

N_a = normal reaction force at at the armature
N_b = normal reaction force at the bourrelet
ℓ = distance between c. g. and base of armature
h = distance between bourrelet and c. g.
R = bore or armature radius
r = bourrelet radius
δ_b = contact point deformation at the bourrelet, normal to bourrelet
ε = projectile c. g. eccentricity
θ = cocking angle of projectile

The deformation at the bourrelet and the friction forces will be determined from the friction coefficients and the design or actual contact pressure at the armature-rail, armature-insulation, bourrelet-rail, and bourrelet-insulation interface. It is difficult to determine them and some simplified approximations from experiments are recommended. The equations are derived from geometrical conditions, force reactions, bourrelet deformation, and the friction law as follows:

$$f_{ar} = 2\mu_{ar} R b p_r \beta \tag{5a}$$

$$f_{ai} = 2\mu_{ai} R b p_i (\pi - \beta) \tag{5b}$$

$$f_a = \mu_{ar} N_a \tag{5c}$$

$$f_b = \mu_b N_b \tag{5d}$$

$$\delta_b = N_b / k \tag{5e}$$

where

μ_{ar} = friction coefficient of armature on rail
μ_{ar} = friction coefficient of armature on insulation
μ_b = friction coefficient of bourrelet on rail
b = width of armature circumferential contact
p_r = contact pressure between armature and rail
p_i = contact pressure between armature and insulation
β = angle subtended by rail with respect to barrel center
k = spring constant at the bourrelet-barrel contact point
π = 3.141593
R = radius of barrel bore

However, these frictions may be ignored if the coefficients of friction are low, which is the usual case.

The drag force of air resistance may be computed from the aerodynamic drag equation

$$D = .5\rho A C_D v^2 \tag{6}$$

where

ρ = air density
A = bore cross-sectinal area = πR^2
C_D = drag coefficient
v = axial velocity of projectile

Lorentz force may be computed from the following formula using rail current and inductance values

$$F = .5L'I^2 \tag{7}$$

where

L' = rail inductance per unit length
I = rail current

However, more complicated Lorentz force formulations may be used when they are available.

In this simple analysis all bodies are considered to be rigid except the bourrelet-barrel contact point. The impact effect is ignored. Therefore, the cocking angle, θ, may be computed from the equation

$$R = (h + \ell)\sin\theta + (r - \delta_b)\cos\theta \tag{8}$$

The axial or x-direction velocity, v, and the travel or displacement, x, of the projectile are the first and second integration of acceleration with respect to time respectively. They are

$$v = \int_0^{t_1} a\,dt \tag{9}$$

$$x = \int_0^{t_1} v\,dt \tag{10}$$

Solutions of Governing Equations

The above-derived governing equations are, in general, solved with numerical methods. A closed form solution is available only in simple or simplified cases.

Substituting the friction equation 5 and the drag equation 6 into the equilibrium equation 1, it becomes

$$a = [F - 2\mu_{ar}Rbp_r\beta - 2\mu_{ai}Rbp_i(\pi - \beta) - \mu_{ar}N_a - \mu_b N_b - .5\rho AC_D v^2 \\ - mg\sin\alpha]/m \tag{11}$$

If the α angle is small then equation 11 may be reduced to the following form

$$a = [F - 2\mu_{ar}Rbp_r\beta - 2\mu_{ai}Rbp_i(\pi - \beta) - \mu_{ar}N_a - \mu_b N_b - .5\rho AC_D v^2]/m \tag{12}$$

To get the upper bound of the acceleration, the friction and drag forces may also be ignored. Consequently, equation 12 becomes

$$a = F/m \tag{13}$$

Many engineers and scientists use this formula, although the computed result is usually 20 to 40 percent larger than obtained from experimental data. Sometimes an empirical correction factor, C, is used which represents the effect (in proportion to Lorentz force) of the sum of the frictions and gravity forces on the right-hand side of equation 11, to reduce the magnitude of the propulsion force in order to make the computation agree with the experimental result. The value of C ranges approximately 0.2 to 0.4. Using the correction factor, C, the equation becomes

$$a = F(1 - C)/m \tag{14}$$

Under the same condition of ignored friction and drag forces and the small mass of projectile package, equations 2 and 3 may be reduced to

$$0 = N_a - N_b \tag{15}$$

$$0 = yF - N_a(\ell\cos\theta - R\tan\theta - \varepsilon\sin\theta) \\ - N_b[h\cos\theta + \varepsilon\sin\theta - (r - \delta_b)\sin\theta] \tag{16}$$

Substituting equations 4, 5e, 7, and 15 into equation 16, the normal force N_a is solved from the following quadratic equation

$$N_a^2 \sin\theta/k + N_a [(\ell + h)\cos\theta - R\tan\theta - r\sin\theta]$$

$$- .5L'I^2(\ell \sin\theta + \varepsilon\cos) = 0 \tag{17}$$

Therefore

$$N_a = -\frac{B}{2A} \pm \frac{\sqrt{B^2 - 4AE}}{2A} \tag{18}$$

where

$$A = \sin\theta/k \tag{19a}$$

$$B = (\ell + h)\cos\theta - R\tan\theta - r\sin\theta \tag{19b}$$

$$D = - .5L'I^2(\ell \sin\theta + \varepsilon\cos\theta) \tag{19c}$$

Having N_a solved, N_b and δ_b are

$$N_b = N_a \tag{20a}$$

$$\delta_b = N_a/k \tag{20b}$$

Further simplification may be done by noticing that $\sin\theta$ is small and k is large. Hence, equation 17 becomes

$$N_a = -E/B \tag{21}$$

Sample of Computation

A simple example without friction or air drag forces is presented here which requires only limited essential data. This example shows the variation of the cocking angle with the propulsion force. More complicated cases may be solved with numerical techniques, if more data were available, and more accurate results were required.

The given data for this example are

Barrel length = 4.0 m
Bore radius = 2.5 cm
Bourrelet radius = 2.4 cm
Armature base distance to c. g. of projectile = 2.5 cm
Bourrelet distance to c. g. of projectile = 2.5 cm
Projectile c. g. eccentricity = 0.1 cm
Bourrelet-rail contact spring constant = 5 E+6 N/m
Mass of projectile package = 0.005 kg
Rail inductance = 0.35 μH/m
Rail current versus time curve as shown in figure 3

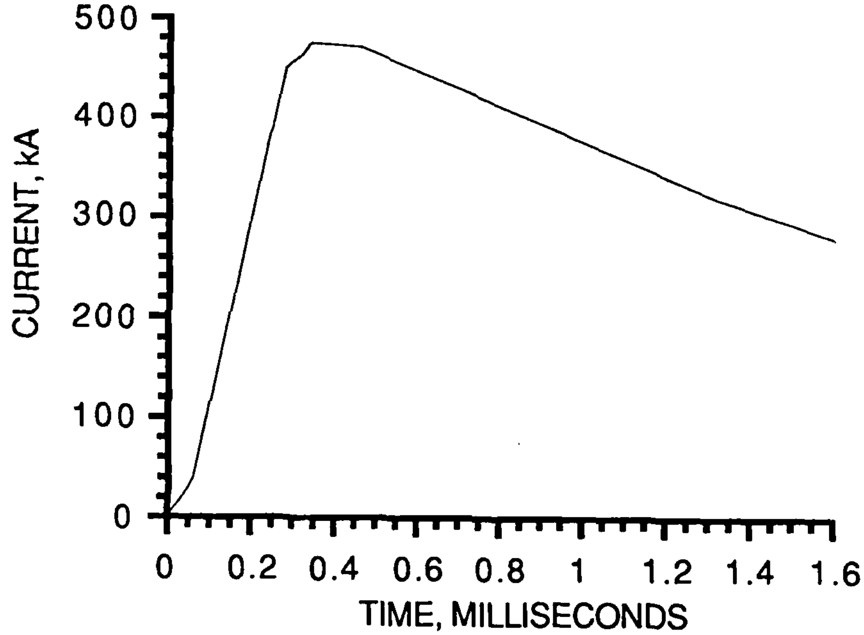

Figure 3. Rail current versus time

Using these values and the derived equations, the normal reaction force, the bourrelet deformation and the cocking angle were computed and shown in figures 4 through 9. Axial acceleration, velocity and displacement of the projectile package are the same as shown in the reference since the same data were used and friction and air drag forces were neglected. The procedure is not repeated here but figures 10 through 14 are shown to give a complete idea of the cocking condition and axial motion during projectile in-bore motion.

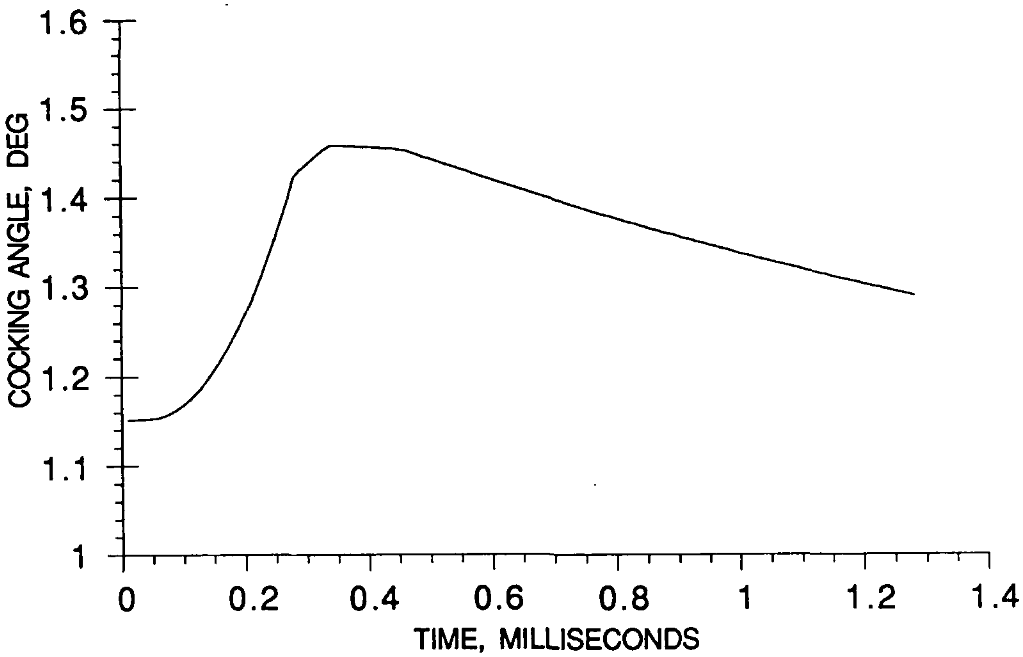

Figure 4. Cocking angle versus time

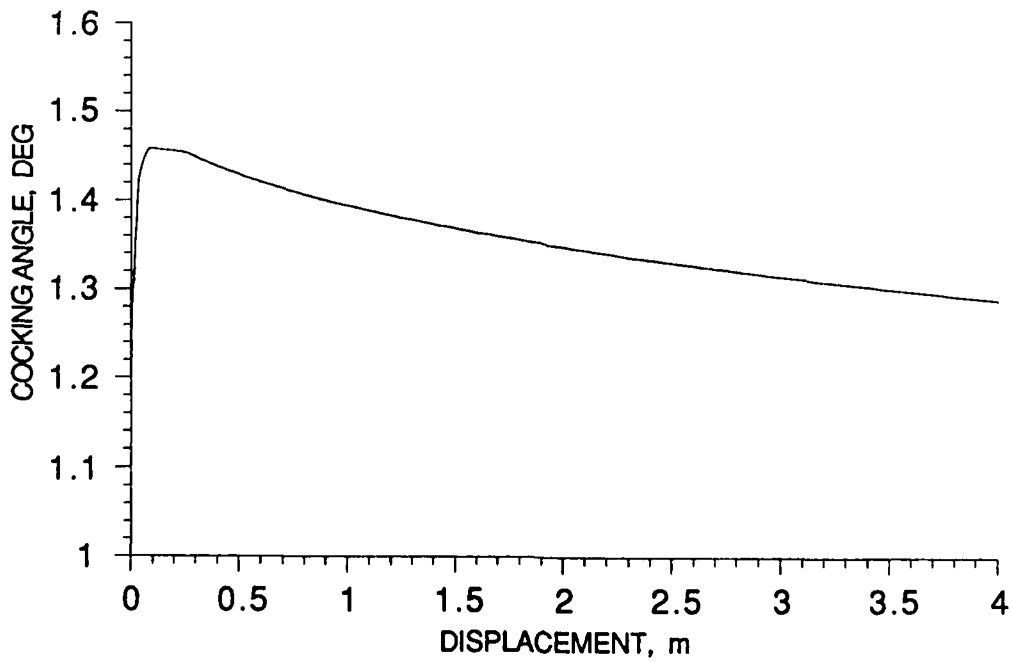

Figure 5. Cocking angle versus displacement

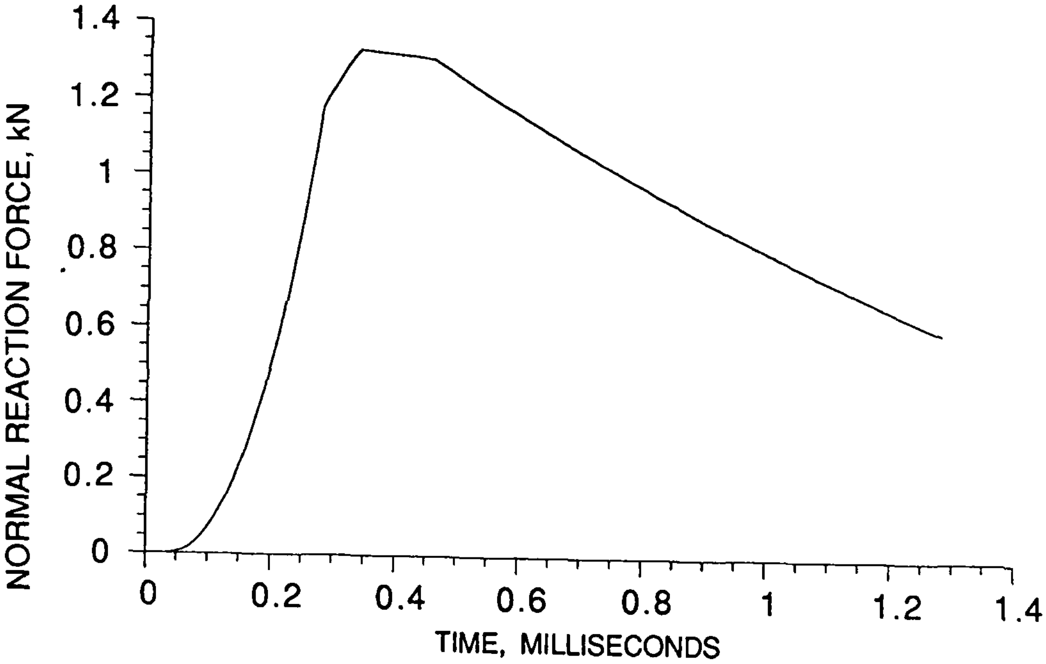

Figure 6. Normal reaction force at armature and bourrelet versus time

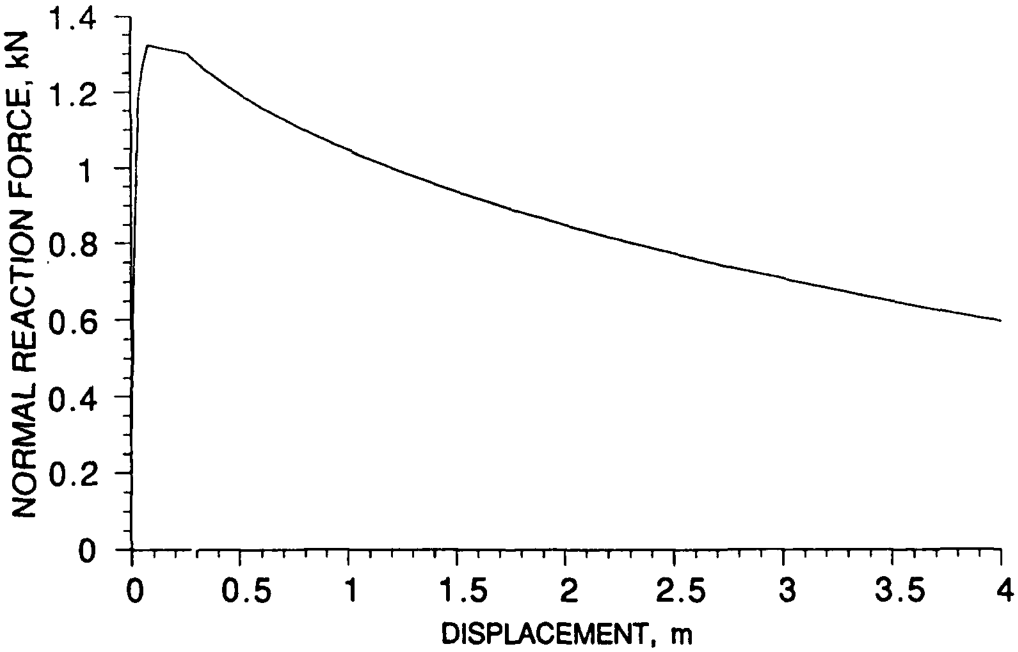

Figure 7. Normal reaction force at armature and bourrelet versus displacement

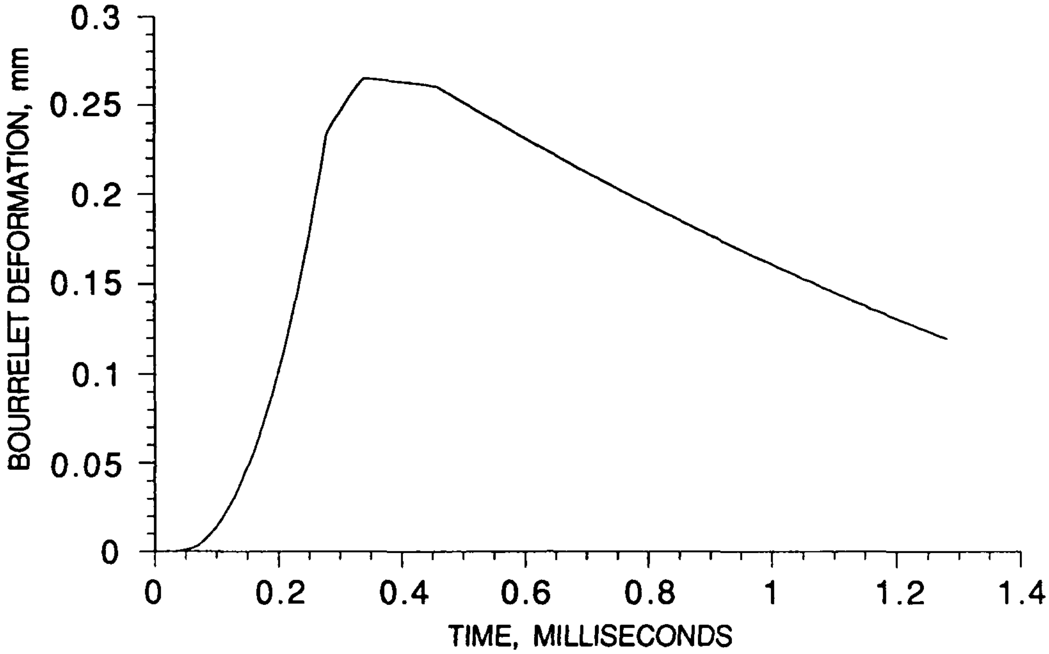

Figure 8. Bourrelet deformation versus time

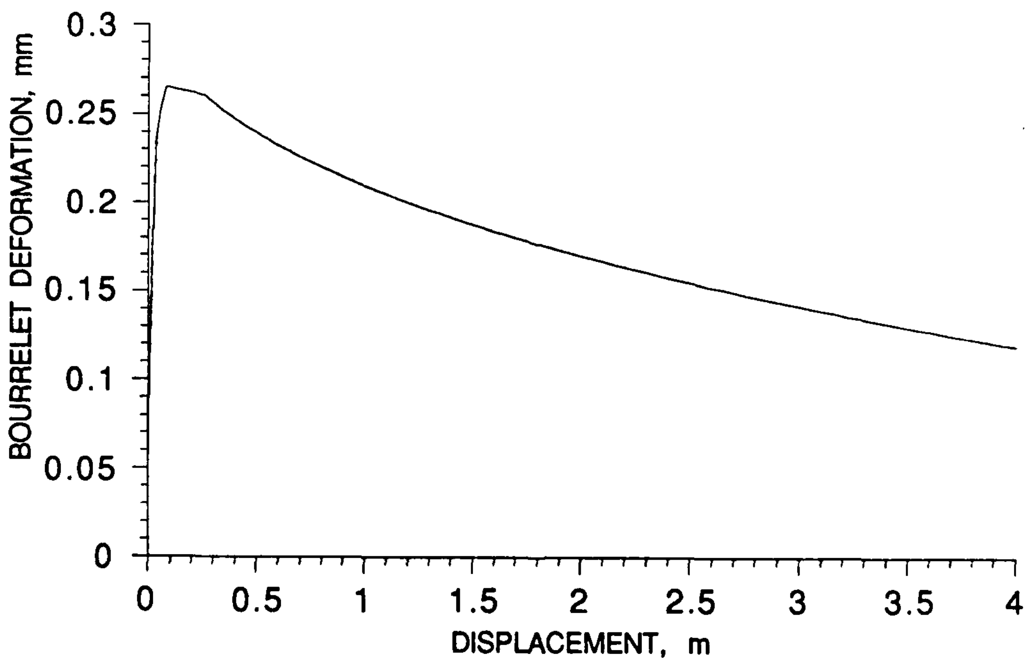

Figure 9. Bourrelet deformation versus displacement

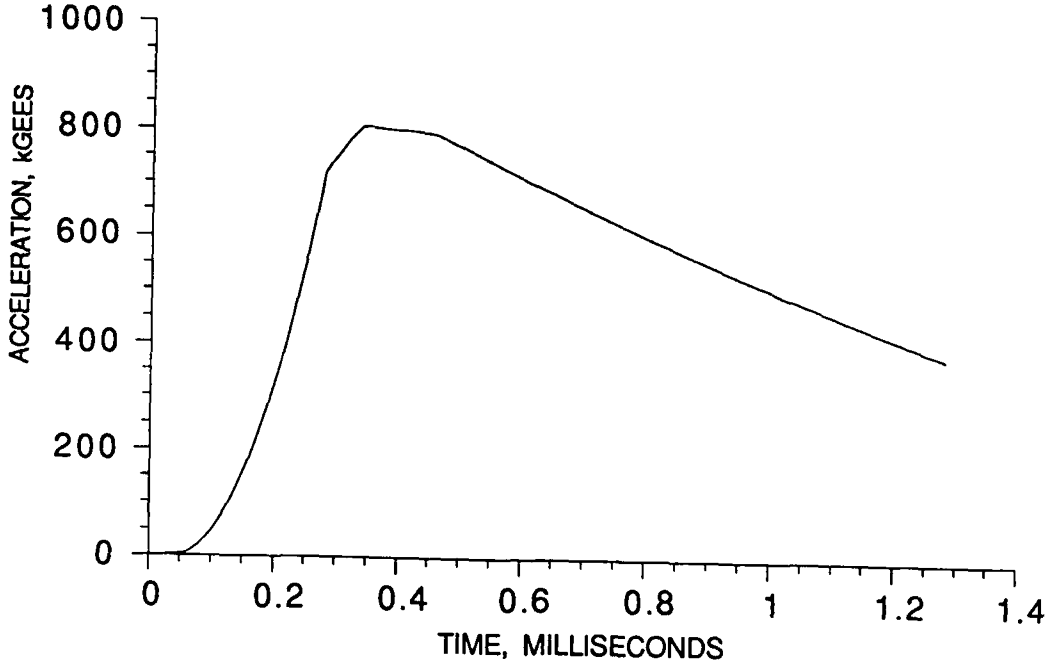

Figure 10. Axial acceleration versus time

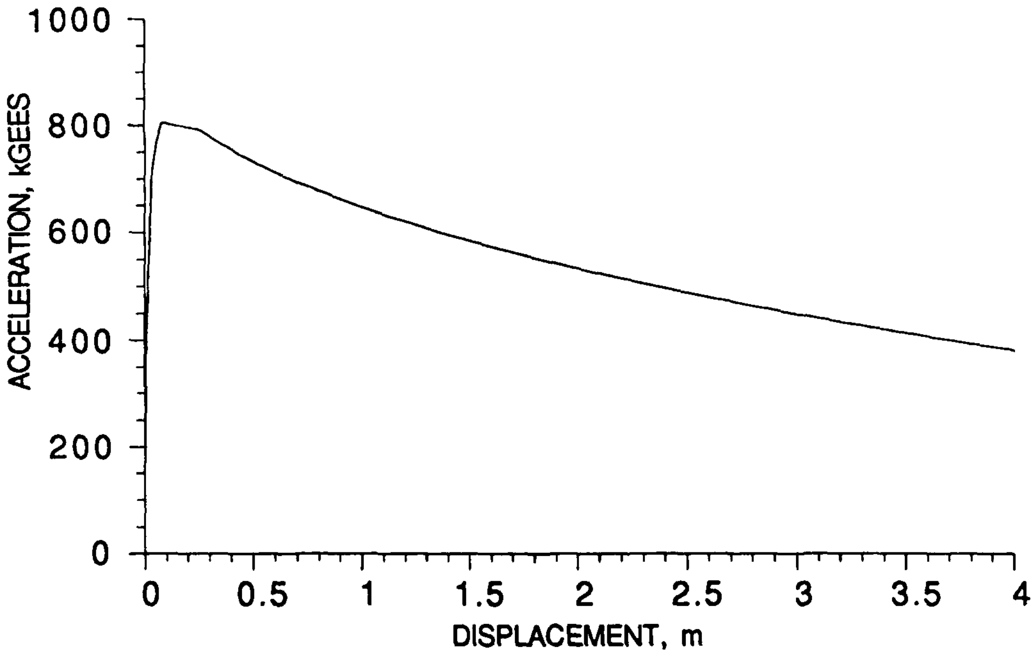

Figure 11. Axial acceleration versus displacement

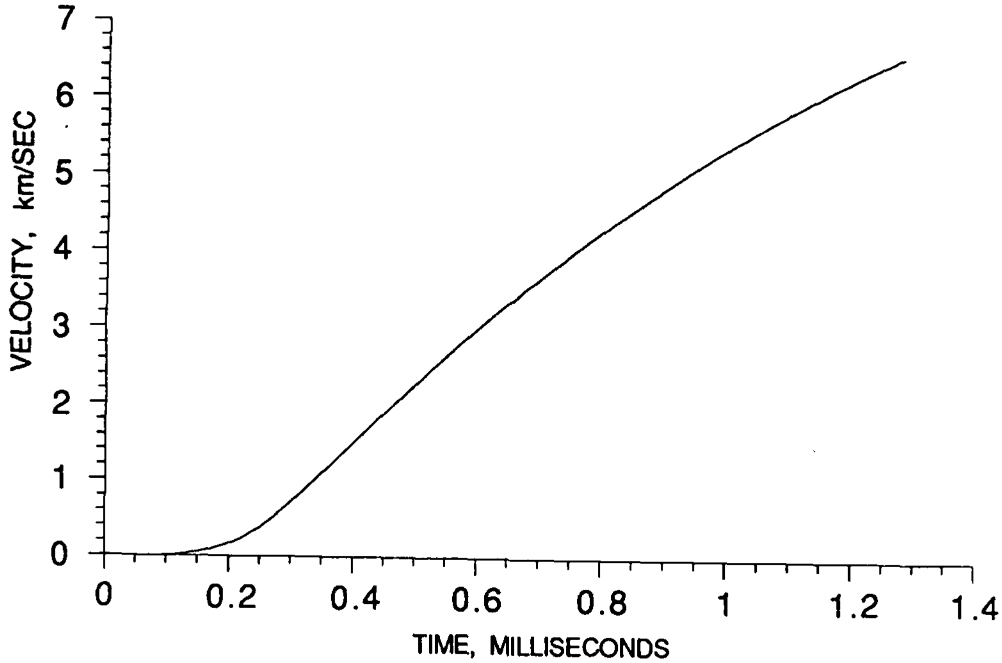

Figure 12. Axial velocity versus time

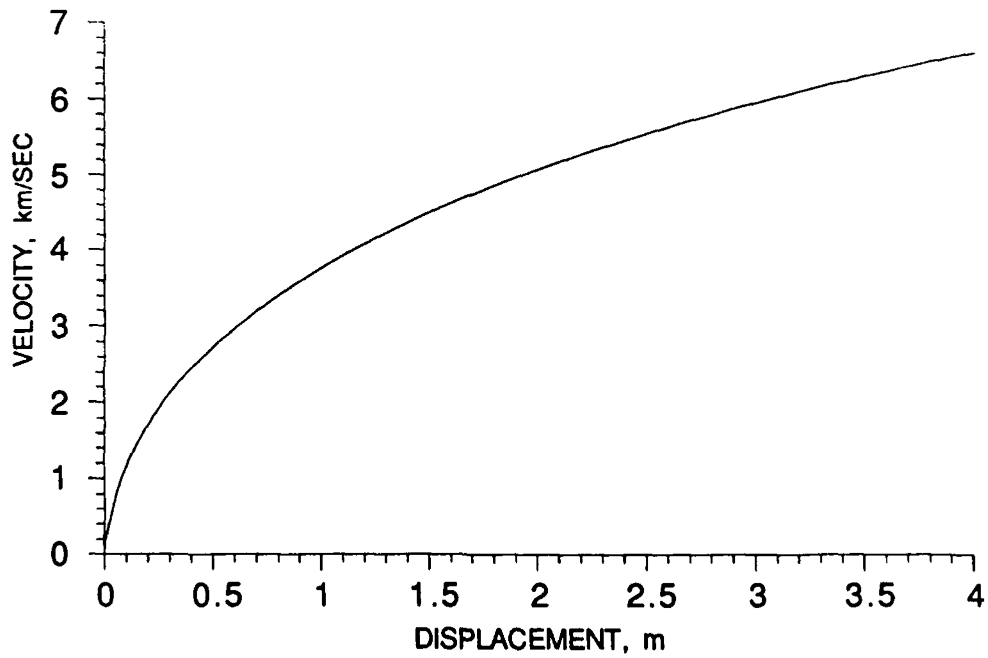

Figure 13. Axial velocity versus displacement

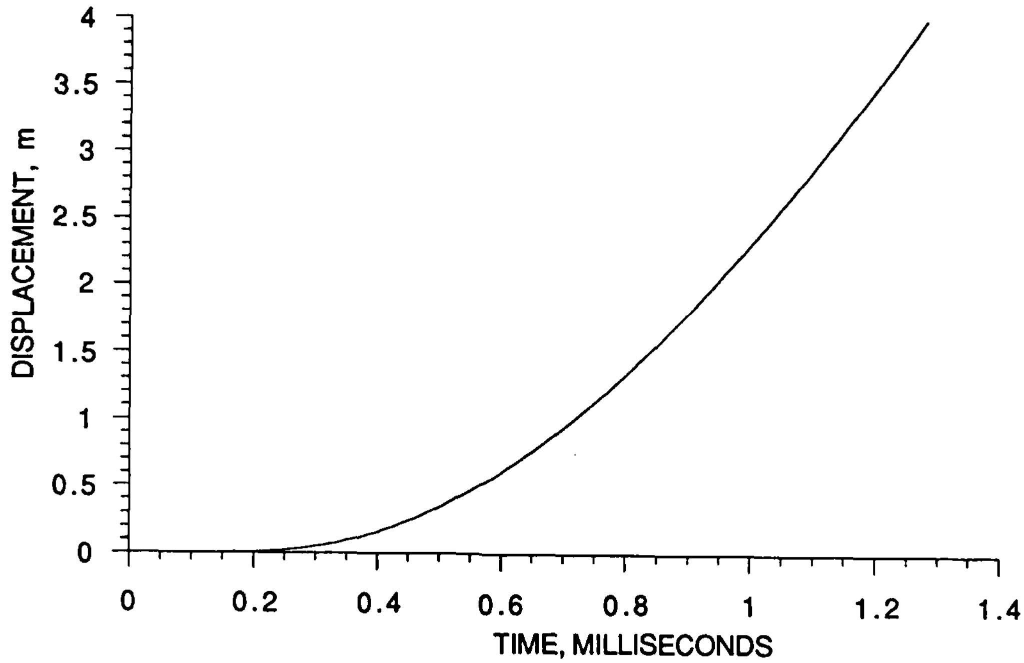

Figure 14. Displacement versus time

CONCLUSIONS

In this second of three basic reports on the in-bore forces and motions of electromagnetic railguns, a set of simple basic balloting equations has been derived to compute the cocking angle of the projectile package (armature and projectile) in addition to its axial acceleration, velocity and displacement as it is launched. Reaction forces at the armature and bourrelet contact regions were also computed. Consequently the associated curves with respect to time and displacement give some basic idea of the balloting motion of the projectile inside an electromagnetic railgun.

REFERENCE

Chu, Szu Hsiung, "A Basic Simple Modeling of In-bore Motion of Railgun Projectiles," Technical Report ARFSD-TR-90028, ARDEC, Picatinny Arsenal, NJ, 1991.

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